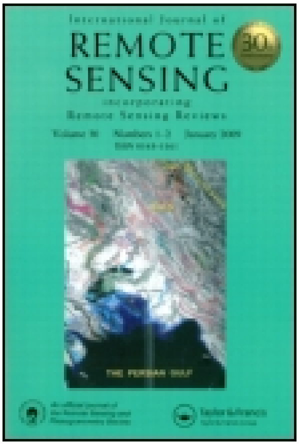

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

Modelling of crop growth conditions and crop yield in Poland using AVHRR-based indices

K. Dabrowska-Zielinska, F. Kogan, A. Ciolkosz, M. Gruszczynska & W. Kowalik

Available online: 25 Nov 2010

INT. J. REMOTE SENSING, 2002, VOL. 23, NO. 6, 1109–1123

Taylor & Francis
Taylor & Francis Group

Modelling of crop growth conditions and crop yield in Poland using AVHRR-based indices

K. DABROWSKA-ZIELINSKA†, F. KOGAN‡*, A. CIOLKOSZ†, M. GRUSZCZYNSKA† and W. KOWALIK†

†Remote Sensing and Spatial Information Centre, 2/4 Jasna St. 00-950, Warsaw, Poland; e-mail: kasia@igik.edu.pl
‡NOAA/NESDIS, Satellite Research Laboratory, Washington, DC 20233, USA; e-mail: fkogan@nesdis.noaa.gov

(*Received 28 February 2000; in final form 5 January 2001*)

Abstract. The application of satellite-derived indices for assessment of crop growth conditions in semi-arid countries is well known. In this paper the authors describe the application of these indices outside semi-arid areas, in Poland, a country with a sufficient water supply. Two indices, Vegetation Condition Index (VCI) and Temperature Condition Index (TCI), were computed for the whole country for each week for a period of 14 years. These indices were correlated with cereal yield anomalies for each of 49 regions of Poland. Two critical periods in crop development were found: early spring (14–16 weeks of the year) and early summer (22–25 weeks) when the state of crop development determines the magnitude of yield. The indices computed for these two periods were used in a yield prediction model. The results were compared with data provided by the Central Statistical Office. The average error of cereal yield estimates for 49 regions was lower than 4%.

1. Introduction

Agricultural production in Poland is the main source of income for nearly 12% of the population, providing food for the 40 million people of the entire country and contributing to the gross national product through the export of live animals, animal and vegetable products, and prepared foodstuffs. The production of basic consumer cereals is to a considerable extent weather dependent and in some years is not sufficient for the needs of the country. Therefore, assessment of cereal production well in advance of harvest is a very important issue for the Polish economy as it has an influence on the planned import quota.

The Central Statistical Office assesses the potential yield of the main crops every year. Agricultural experts working for this Office perform the preliminary, pre-final and final assessment of crops in July, September and November, respectively. In preparation of preliminary assessment they use their knowledge and experience to make visual observations of crop development. They also make biometric measurements of crops. In pre-final assessment, agricultural experts also take into consideration meteorological conditions during the growing season as well as historical observations of agrometeorological conditions and their influence on yield. The final

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2002 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160110070744

assessment is done on the basis of expertise of agricultural experts and investigations done in 30 000 points. Some additional remarks of independent agricultural corespondents are also taken into account. The final result of assessment of main crop yield is done with a relative standard error of less than 1%. The results of these predictions are published in official bulletins and delivered to the Ministry of Agriculture and other governmental and local authorities throughout Poland.

The method of visual crop condition evaluation in the preliminary and pre-final assessments of crop yield is being influenced to a considerable extent with subjective approach. In addition, the procedure of data collection in the field and subsequent data processing is labour- and time-consuming. Therefore, the Polish Remote Sensing and Spatial Information Centre in co-operation with NOAA/NESDIS, Satellite Research Laboratory in Washington, have undertaken the research to explore remote sensing methods of crop growth conditions and yield assessments. The method, which has been shown to be very useful in arid and semi-arid areas (Kogan 1997, Unganai and Kogan 1998), was applied for the first time outside semi-arid areas, in Poland, a country with a sufficient water supply. The remote sensing method based on application of indices derived from NOAA/AVHRR satellite images was used in the project in order to evaluate the crop stage development and conditions of crop growth.

Specific objectives of the work included: (1) validation of Advanced Very High Resolution Radiometer (AVHRR)-derived indices in relation to cereal growth conditions in Poland; and (2) modelling the yield of basic cereals versus the vegetation indices.

2. Environmental features

Poland is situated in the Great European Plain between the Baltic Sea and the Carpathian and Sudety Mountains. Lowland, highlands and mountainous terrains cover 91.3%, 7.7% and 1% of the area of the country, respectively. Most of Poland has light soils of podsolic origin and 75% of them are of inferior quality. Although arable land covers about 65% of Poland, only every fourth hectare can be used for production of such major crops as wheat, barley, sugar beets, rapeseeds and vegetables which require high quality soils.

Poland is located in the region where precipitation had surpassed transpiration, but since the end of the 1960s one can observe a decrease of rainfall by about 70 mm, so much, that some regions of the country have started to suffer from an insufficient amount of water. In comparison to other European countries Poland has the least favourable water system. Water deficit is observed in the central belt of Polish lowland. According to statistical data from the 1970s, acreage of overdried agricultural land measured about 4 million ha (about 20% of the total). The poor condition of the land is caused by extensive deforestation done in the past as well as by mistakes made in water resource management. There is no crop irrigation system in Poland. Due to shortage of precipitation especially during the growth season, harsh winters, strong spring temperature fluctuation, lack of warm weather in the summer, the yield of many crops can vary considerably (table 1).

Private farms dominate in Polish agriculture and most of them (85%) are operated by one family. In the last 20 years the average area of private farm increased from 6.5 to 7.8 ha. However, there are still some 2 million private farms with an average size less than 6 ha and about 1.5 million with size even less than 1 ha. Liquidation of state farms and substantial reduction in the number of agricultural

Table 1. The average yield (dt ha^{-1}) of some basic crops in Poland.

	Year								
Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998
Wheat	39.6	38.0	30.6	33.3	31.8	37.8	35.6	32.5	36.2
Rye	26.1	25.8	19.6	22.6	21.8	25.6	23.4	23.1	24.7
Barley	35.9	34.4	23.5	27.9	26.0	38.8	29.0	32.0	31.7
Potatoes	198.0	168.0	133.0	206.0	136.0	164.0	203.0	159.0	200.0
Sugar beets	380.0	316.0	294.0	392.0	292.0	346.0	394.0	379.0	379.0

co-operative and collective farms favourably affected the size structure of private farms and increased their importance in agricultural production. In 1995 private farms covered about 82% of arable land in Poland.

3. Data

The Global Area Coverage (GAC) data created onboard of the NOAA satellite have been used in the investigation of crop growth conditions based on low-resolution satellite images. GAC contains one out of three original AVHRR lines and data resolution is further reduced by averaging every four adjacent samples and skipping the fifth sample along the scan line. GAC data are usually referred to as 4 km spatial resolution (Kidwell 1996). GAC data were a basis for creation of Global Vegetation Index (GVI) by sampling and mapping 4 km daily radiances in the visible (VIS; 0.58–0.68 μm), near-infrared (NIR; 0.72–1.1 μm) and infrared (IR; 10.3–11.3 and 11.5–12.5 μm) parts of electromagnetic spectrum. The registered radiances were truncated to 8-bit precision and mapped to a (16 km^2) latitude/longitude grid. Since AVHRR-based radiances have both inter-annual and intra-annual noise (variable illumination and viewing conditions, sensor degradation, satellite navigation and orbital drift, atmospheric and surface conditions, methods of data sampling and processing, communication and random errors) its removal is crucial for data use. The initial processing included post launch calibration of VIS and NIR channels (Rao and Chen 1995, 1999) calculation of Normalized Difference Vegetation Index ($NDVI = (NIR - VIS)/(NIR + VIS)$), and converting the Ch4 radiance to brightness temperature (BT), which was corrected for non-linear behaviour of the sensor (Weinreb *et al.* 1990, Kidwell 1996). The processing of NDVI and BT included complete removal of temporal high frequency noise using temporal median filter. Additional concern is BT decrease due to satellite orbit degradation with the ageing of satellites. Our investigations showed that in vegetated areas the errors due to temperature decrease are much smaller than variation of temperature during the growth season due to drought and non-drought events. Therefore, the correlation of temperature with crop yield may be strong.

In presented studies the high resolution Landsat Thematic Mapper (TM) images have also been used. These images were applied to differentiate between arable land and other land use categories (built-up areas, forests, natural vegetation covered areas and inland waters). On the basis of these images, a mask of arable land has been created for the whole country.

The Central Statistical Office of Poland provided data on yield of main cereal crops (rye, wheat, barley, and corn) for each of voivodship (first order's units of the administrative division in Poland) for period of 1985–1998. Meteorological observations (air temperature and precipitation) were obtained from the Institute of Meteorology and Water Management. These data were collected in 60 meteorological stations spread throughout the country.

4. Method

On the basis of GVI two other indices, Vegetation Condition Index (VCI) calculated from NDVI and Temperature Condition Index (TCI) calculated from brightness temperature (BT), have been obtained in order to detect medium-to-low frequency fluctuations in vegetation condition associated with weather variations (Kogan 1997). In order to minimize cloud effects, NDVI and BT values were composited over a 7-day period by saving those values that had the largest difference between visible and near-infrared reflectance. After temporal smoothing NDVI and BT were normalized to the range of their change in the database according to the formulas:

$$\mathrm{VCI}=100\,\frac{\mathrm{NDVI}-\mathrm{NDVI}_{\mathrm{min}}}{\mathrm{NDVI}_{\mathrm{max}}-\mathrm{NDVI}_{\mathrm{min}}} \tag{1}$$

$$\mathrm{TCI}=100\,\frac{\mathrm{BT}_{\mathrm{max}}-\mathrm{BT}}{\mathrm{BT}_{\mathrm{max}}-\mathrm{BT}_{\mathrm{min}}} \tag{2}$$

where NDVI is the smoothed weekly NDVI; $\mathrm{NDVI}_{\mathrm{max}}$ and $\mathrm{NDVI}_{\mathrm{min}}$ are the multiyear absolute NDVI maximum and minimum, respectively; BT is the smoothed weekly radiant temperature derived from channel 4 of AVHRR; and $\mathrm{BT}_{\mathrm{max}}$ and $\mathrm{BT}_{\mathrm{min}}$ are the multiyear absolute BT maximum and minimum respectively. These indices change from 0 to 100, reflecting changes in vegetation conditions from extremely poor to optimal.

Since GVI pixels represent the areas larger than agricultural plots, first, we investigated whether low-resolution pixels characterized arable areas adequately. A Landsat TM-derived map presenting distribution of agricultural areas was used for this purpose. A grid of TCI and VCI pixels was overlaid on this map and the percentage of arable land in each pixel was calculated. The pixels were grouped into two classes: the first one contained pixels covering from 50% to 100% of agricultural land, the second class contained pixels covering less than 50% of agricultural land. From among the pixels of the first class a subgroup of pixels covering from 70 to 100% of agricultural land was distinguished.

More than 76% of the total area of the country was covered by the TCI and VCI pixels containing up to 50% of agricultural land. The remaining part of the total surface of Poland was covered by the pixels containing from 50 to 100% of agricultural land. In this upper range only 8% of area of Poland was covered by pixels containing 70–100% of agricultural land. The detailed analysis of the relation between average TCI and VCI values and the share of agricultural land in particular pixels, performed for 14 years, revealed that for the main part of the growth season (weeks 14–25) there was no significant difference in the values of TCI and VCI computed for the pixels containing various percentage of the agricultural land (an example of the computations for 2 years of extremely different yield is given in figure 1). This indicates that mean values of VCI and TCI computed for the entire voivodship or entire country may be used to represent agricultural areas and there is no need to mask the arable land for further analysis. The spatial averages of these

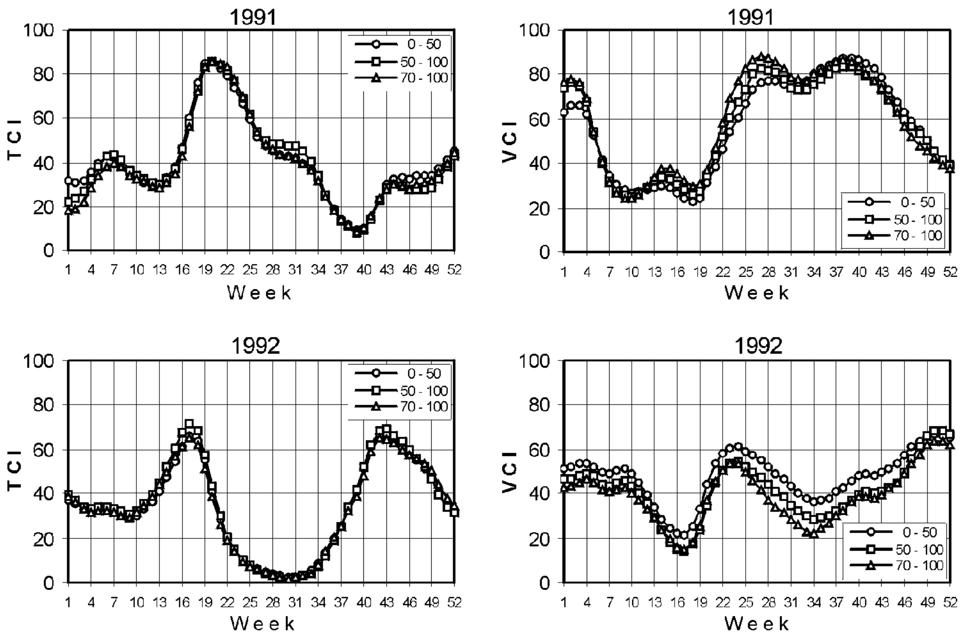

Figure 1. Average TCI and VCI values for pixels containing various percentage of agricultural land for two chosen years.

two indices have been computed for each week from 1985 to 1998 for all 49 voivodships.

5. Estimation of vegetation conditions

VCI has been based on relation between current weekly value of NDVI and the values of NDVI that represent the best and the worst growth conditions of crops in each week in the period of 14 years (1985–1998). TCI represents the relation between current weekly values of bright temperature (BT) and bright temperatures which occurred during potential and stress crop conditions within the same period. Both indices have been used to assess crop growth conditions every year from early spring to late summer. During the entire period of research, different crop growth conditions have occurred in Poland, resulting in different cereal yields. In this investigation cereal yield was expressed as a deviation from 14-year mean (technological trend was not observed in this period). As seen in figure 2, cereal yield deviation from multiyear mean fluctuates significantly due to weather variations. The two highest and the two lowest yield years were 1990, 1991 and 1992, 1994, respectively. For further analysis of vegetation conditions based on satellite and ground data two extremely different years: 1991 ($Y/Y_{mean}=109\%$) and 1992 ($Y/Y_{mean}=82\%$) were selected. Also, two years with close to average crop yield—1997 ($Y/Y_{mean}=97\%$) and 1998 ($Y/Y_{mean}=103\%$)—were chosen (Central Statistical Office 1999). After 1998 the administrative division of Poland was changed and since 1999 the crop yield data for the division considered in this study have not been available from the Central Statistical Office.

Since the value of crop yield depends on weather conditions in the growth season and because VCI and TCI characterize these conditions, yield deviations were

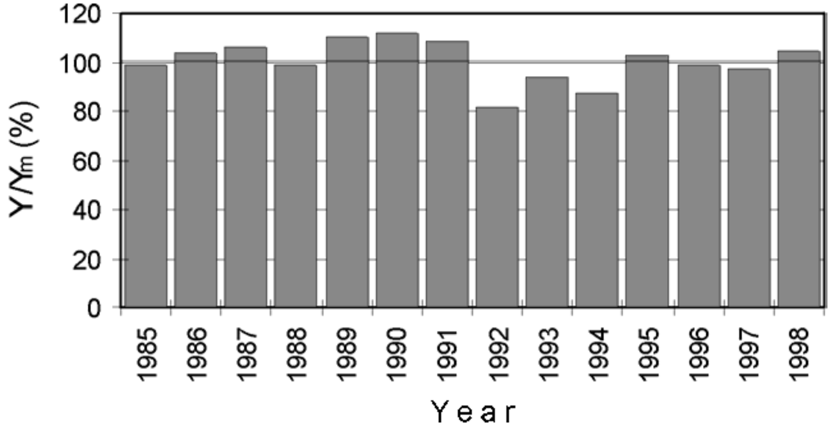

Figure 2. The ratio of current to mean values of cereal yields for the years 1985–1998 for Poland.

correlated with the indices for whole Poland and for each voivodship. The result of correlation for Poland is shown in figure 3 where correlation coefficients between Y/Y_{mean} and TCI are plotted during the main part of seasonal cycle. The two important periods where the correlation is significant are clearly identified in this figure. In the period of early summer (weeks 22–25) correlation is the highest. This period is critical because cereals are going through their reproductive stage when cooler weather is favourable for crop development and yield formation. Another period of considerable correlation is identified in spring (weeks 14–16). The correlation is negative, indicating that cold spring suppresses growth of cereals leading to yield reduction in Poland. The sensitivity of crops on TCI in these periods corresponds to the increase of water demand by plants.

The VCI index also showed some correlations during spring and summer, although the correlations were not as strong as in the case of TCI. The best correlation appeared in week 25 of the year. In semi-arid areas VCI is an important component of crop modelling since it reflects moisture conditions (Unganai and Kogan 1998). It seems that in the areas of positive water balance (annual precipitation exceeds potential evapotranspiration) such as in Poland, VCI plays a minor role in

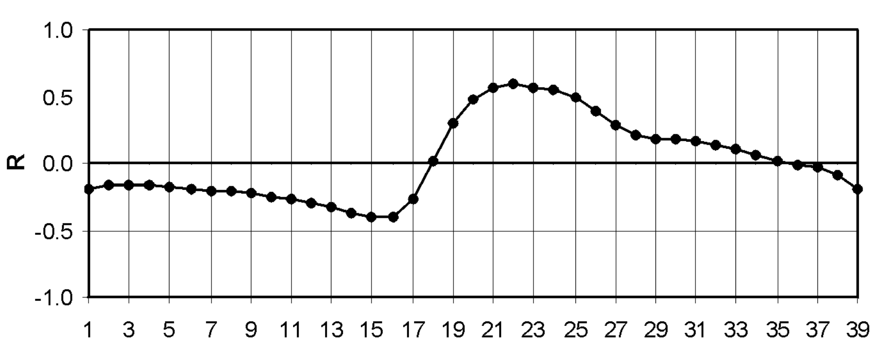

Figure 3. Correlation coefficient (R) of the relationship between Y/Y_{mean} and TCI for weeks 1–39.

diagnosis of crop yield. In investigations performed in Hungary by Hamar *et al.* (1996) a good correlation between yield and Greenness Index (GN) has been found in week 29 of the year (the second part of July). Therefore, application of an index based on temperature like TCI gives the possibility of forecasting yield almost a month earlier.

Figure 4 presents the TCI in four chosen years in all voivodships in Poland from weeks 10 to 35. In 1991 the TCI during the first stage of growth season was low till the week 14. In some voivodships TCI was still low in the next two weeks, but in some other voivodships TCI was quite high. From weeks 19–23 in greater part of voivodships the TCI was high, reaching values of 100 or close to 100. In the majority of the voivodships TCI values started to diminish from week 23 and since week 26 till 35 the decrease of TCI was slower. The low TCI up to week 16 indicated that vegetation conditions for crop development were very good. The different values of TCI in the course of growth season correspond very well to meteorological observations (Institute of Meteorology and Water Management, *Agrometeorological Bulletin* 1991, 1992, 1997, 1998). Figure 5 presents differences between current and mean air temperature and current and mean precipitation in these four chosen years. In 1991 the air temperature until week 15 was about 3° higher than the mean air temperature in Poland (figure 5), what reflected good crop conditions in this growth season (figure 4). At the same time current sum of precipitation was close to the mean (figure 5), and soil moisture due to water retention in winter has been sufficient for crop development.

In the next crucial period (weeks 22–25) the TCI indicated that the brightness temperature was lower than the maximum temperature in this period. It has been interpreted as good vegetation growth conditions. The air temperature from weeks 15–22 was lower than the mean at that time, however the sum of precipitation in weeks 18–20 was much higher than the mean—20 mm above average in week 20 (figure 5). It resulted in very good soil water conditions at that crucial time of vegetation demand of water. In the period between 23 and 26 weeks, the air temperature was near the mean and sum of precipitation was higher than the mean. From 26–40 weeks of the year air temperature was higher than the mean and sum of precipitation lower. At this stage of cereals crop development water demand has been negligible as cereal crops reached maturity.

Different TCI values can be seen in 1992 (figure 4). At the beginning of the growth season, TCI was low (weeks 10–12), however from week 13 it started to increase, reaching the maximum in weeks 16–18. In the following weeks TCI started to decrease, reaching a minimum in some voivodships in week 22 and in all voivodships in weeks 26–34. From week 34 the TCI started to increase again. The mean air temperature in Poland in 1992 (see figure 5) during the first stages of growth season (up to week 20) was only about 1° lower than the mean or very close to it. Such temperature influenced positively cereal growth conditions expressed by high TCI (over 50) in most of the voivodships. Air temperature started to increase from week 20, and in week 22 it was 1.5° C above the mean, still increasing up to 4° C above the mean in week 32. The sum of precipitation in 1992 up to week 15 was higher than the mean for this period. In the next stage of crop development current precipitation was lower than the mean and in weeks 20–22 it was about 6 mm lower and decreased severely till week 30. The increase of temperature and lack of precipitation caused very poor cereal conditions expressed by low values of TCI (close to 0), while the brightness temperature was close to maximum for this time of the year (Dabrowska-Zielinska *et al.* 1998).

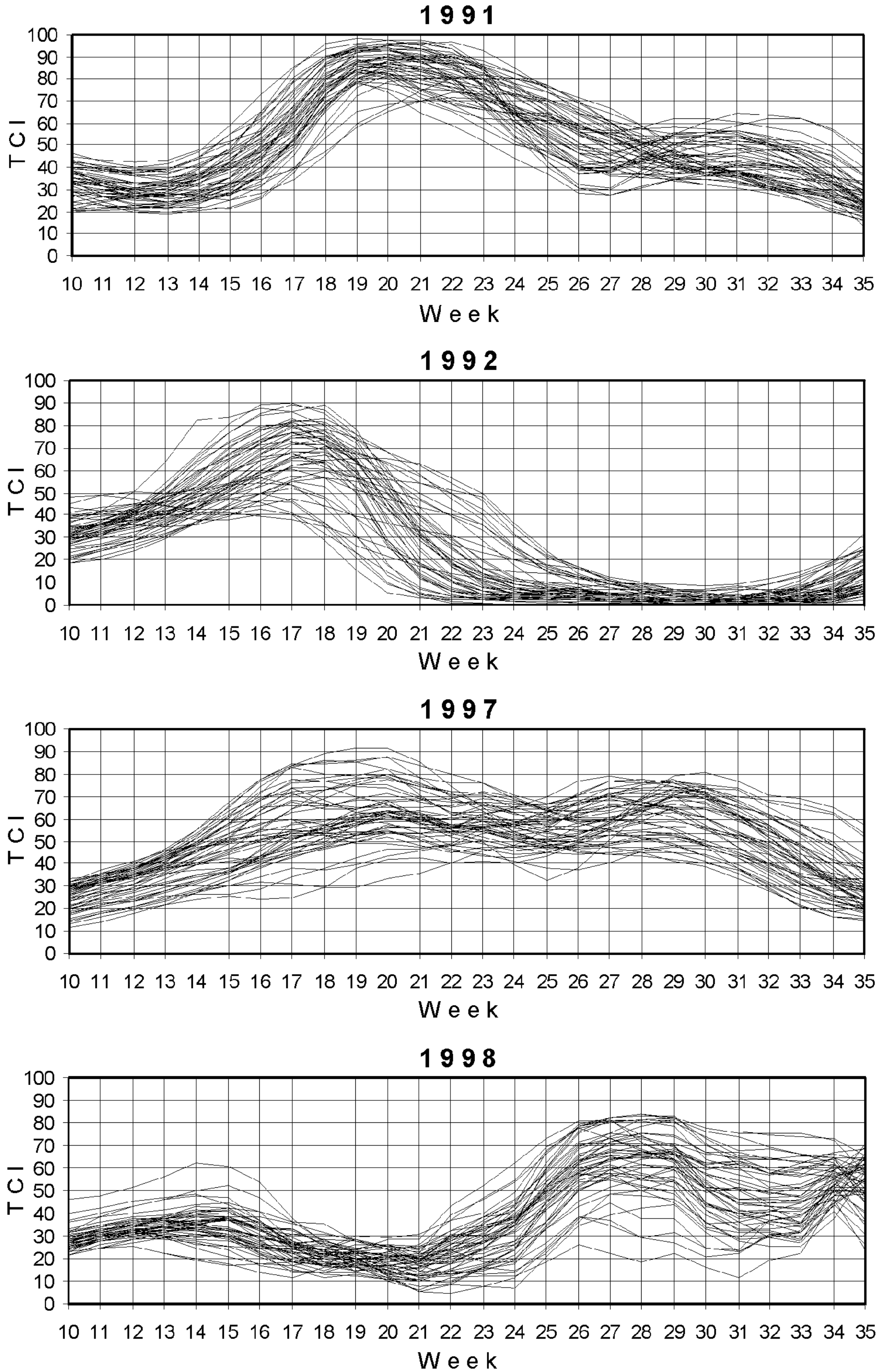

Figure 4. TCI in four chosen years in all voivodships in Poland.

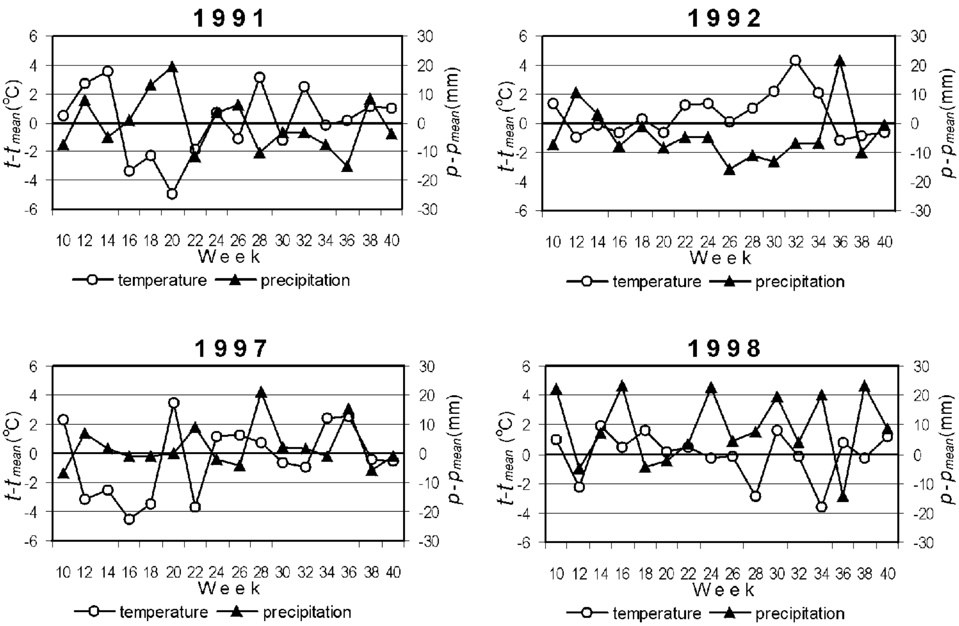

Figure 5. Difference between current and mean air temperature ($t-t_{\mathrm{mean}}$) and current and mean precipitation ($p-p_{\mathrm{mean}}$) in 1991, 1992, 1997 and 1998.

Different crop growth conditions appeared in 1997 (figure 4). At the beginning of the growth season (weeks 10–13) TCI was low (current BT was close to BTmax for that period), which indicated good growth conditions. Air temperature in the whole country at the beginning of growth season (week 10) was 2° C above the mean (figure 5). Later, in weeks 11–18, the average air temperature in the whole country dropped down and was 4° C below the mean. From week 14 TCI started to increase and differed significantly between voivodships from low (below 30) to very high (80) by the week 16. This span in TCI values indicated that crops in particular voivodships experienced various growth conditions from very good to bad. The sum of precipitation was near average in this period (figure 5). In week 22 TCI fluctuated considerably (40–80), indicating variation in cereal conditions from average to very good. After week 23 it was warm with higher precipitation than the mean, especially intensive from week 33 of the year (figure 5).

Figure 4 also shows the TCI in 1998. In early spring up to week 16 the TCI varied from 20 to 60, indicating different crop growth conditions in various voivodships. From that time TCI started to decrease and was almost the same in the majority of the voivodships. TCI values below 40 in that period indicated good conditions for cereal development. The current air temperature in the country in week 12 was lower by about 2° C than the mean at that time. Starting from week 16 up to 24 the air temperature increased and was higher than the mean in that period (figure 5). The precipitation at the beginning of growth season was high (25 mm above the mean in week 16) and from weeks 22 to 35 it was about 20 mm above the mean. The TCI in weeks 22–24 varied from below 10 to 50; it represented various crop growth conditions.

6. Modelling and validation

Analysis of crop growth conditions showed that they might vary significantly from year to year, from season to season, and from region to region. Even in a relatively small country like Poland, located in transition zone between maritime and continental climate, the vegetation growth conditions can be quite different.

Figure 6 represents TCI distribution in all 49 voivodships in Poland in four selected years in two weeks (16 and 22), representing the two most important periods for crop development. At the beginning of growth season of 1991 (week 16), TCI showed considerable variations. In the majority of voivodships it was lower than 50, indicating that crop growth conditions were good in nearly the whole country. In the middle of the growth season (week 22) TCI was high, indicating favourable growth conditions. As a result, cereal yield was one of the highest in the 14-year period (figure 2).

Different growth conditions prevailed in 1992. In early spring TCI was very high all over Poland. Low air temperature in March and April was unfavourable for crop development. In May and June TCI in western and central Poland was extremely low, indicating thermal stress of vegetation, while in eastern Poland TCI was still high, specifying favourable conditions. Unfavourable conditions affected cereal yield, which was the lowest in the 14-year period.

In 1997, cereal yield was close to multi-year average (figure 2). The growth conditions in Poland in early spring of 1997 were not very favourable, which was confirmed by TCI estimates (around 50) in week 16. In late spring (week 22), TCI was also around 50, characterizing average crop growth conditions.

Early spring of 1998 started with low TCI values (below 40) in entire Poland, indicating warm weather and favourable crop conditions. In late spring, conditions deteriorated significantly (low TCI in week 22). However, a significant improvement of growth conditions in June resulted in a slightly above average yield.

Figure 7 presents the spatial distribution of VCI in week 25, which holds stronger information for yield estimates than VCI in weeks 16 and 22. The lowest values of VCI in all voivodships occurred in 1992, a little higher in 1991, and quite high in years 1999 and 1998. After week 22 in 1998 precipitation increased (figure 5), which accelerated vegetation development. The VCI data from this period gave additional information on yield estimates.

Analysis of TCI and VCI in different years at the beginning and in the middle of the growth season suggested that these indices could be applied in models of cereal yield prognosis. Such prognosis could be done at the middle of June, i.e. 4–6 weeks before harvest in Poland. The analysis of significance of TCI and VCI in crop yield assessment showed that the most important are the TCI values in weeks 16 and 22 and the VCI in week 25.

Regression analysis relating yield deviation from mean (Y/Y_{mean}) with TCI in weeks 16, 22 and VCI in week 25 was performed for each of the voivodship. The statistical analysis has been carried out using data from 1985 to 1997.

$$Y/Y_{\mathrm{mean}} = a + b\mathrm{TCI}_{16} + c\mathrm{TCI}_{22} + d\mathrm{VCI}_{25} \tag{3}$$

This model was used for yield prediction for 1998. Yield prediction was issued at the end of June, 4 weeks before harvest. The result of prediction was compared with information on yield estimated performed by the Central Statistical Office (figure 8), published at the beginning of 1999 (Central Statistical Office 1999).

The average error of cereal yield prediction for 49 voivodships was 3.82%. For

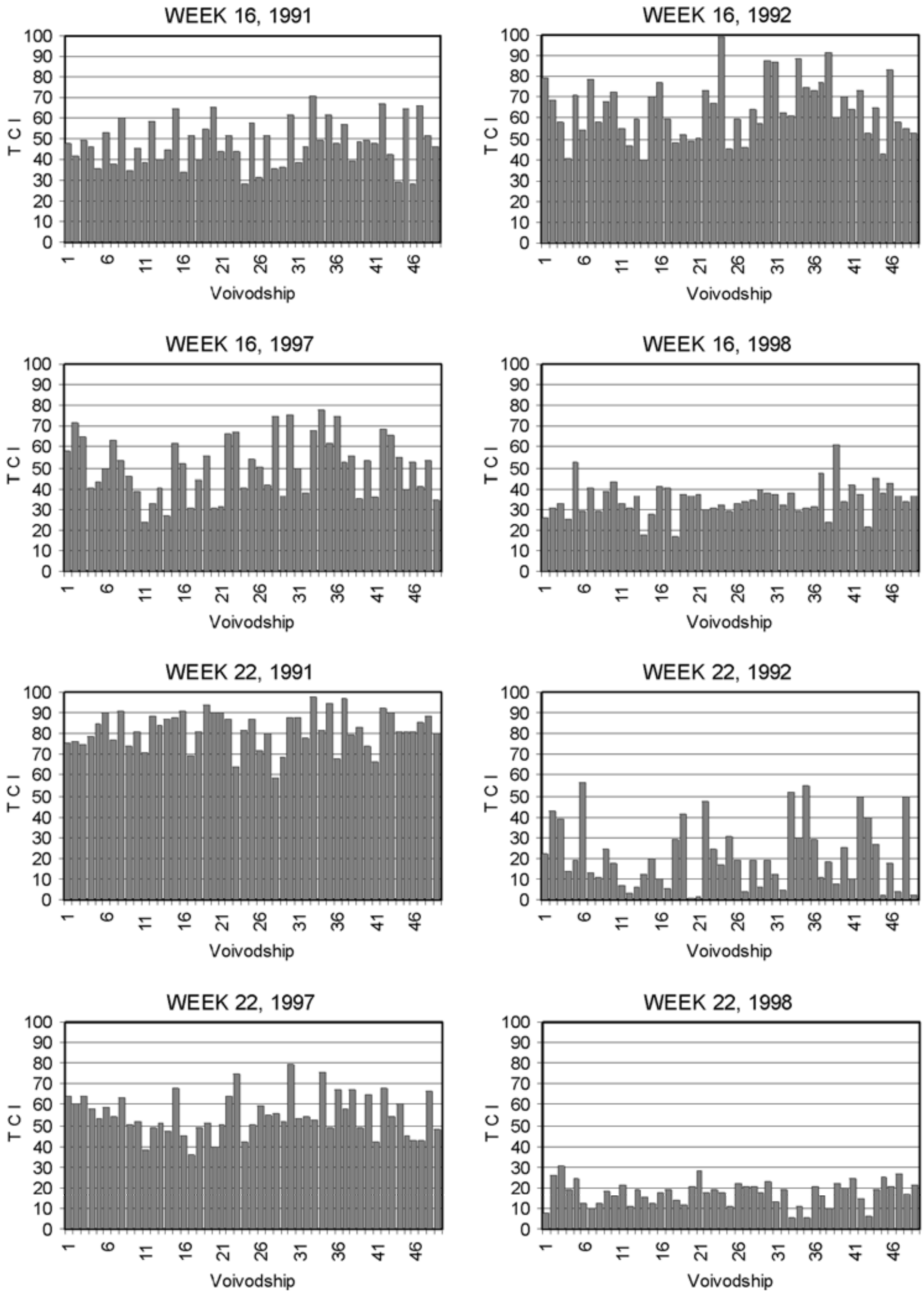

Figure 6. TCI distribution in all 49 voivodships in Poland in two weeks (16 and 22) representing the two most important periods for crop development in four chosen years.

17 voivodships the error was lower than 5% and for 10 the error exceeded 10%. The large error occurred in the case of mountainous, forested and heavy industrialized voivodships. The Central Statistical Office, which is the main forecasting organization in Poland, accepted these results.

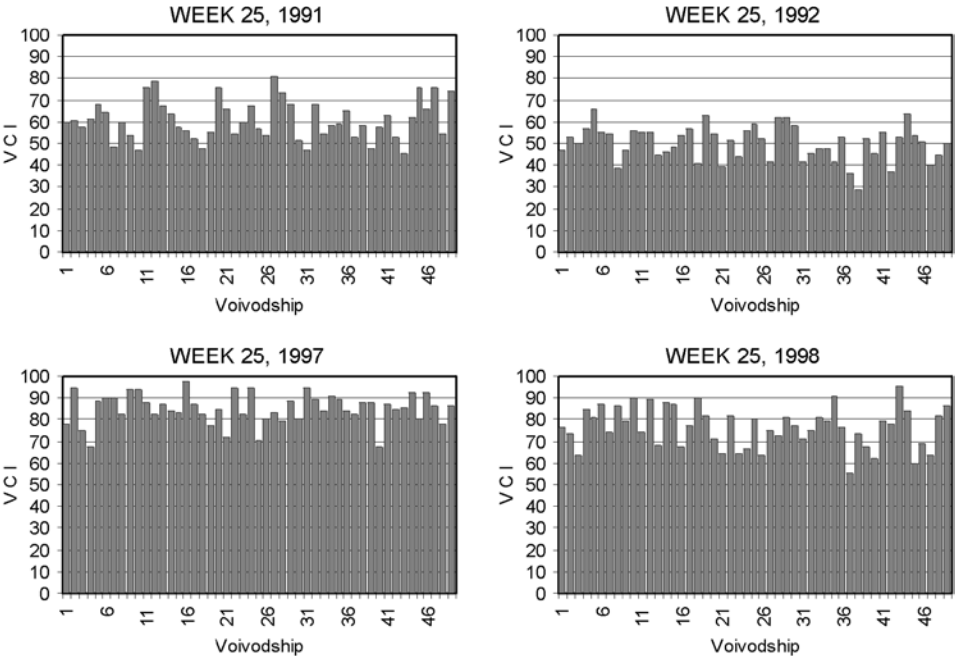

Figure 7. VCI distribution in all 49 voivodships in Poland in week 25 in four chosen years.

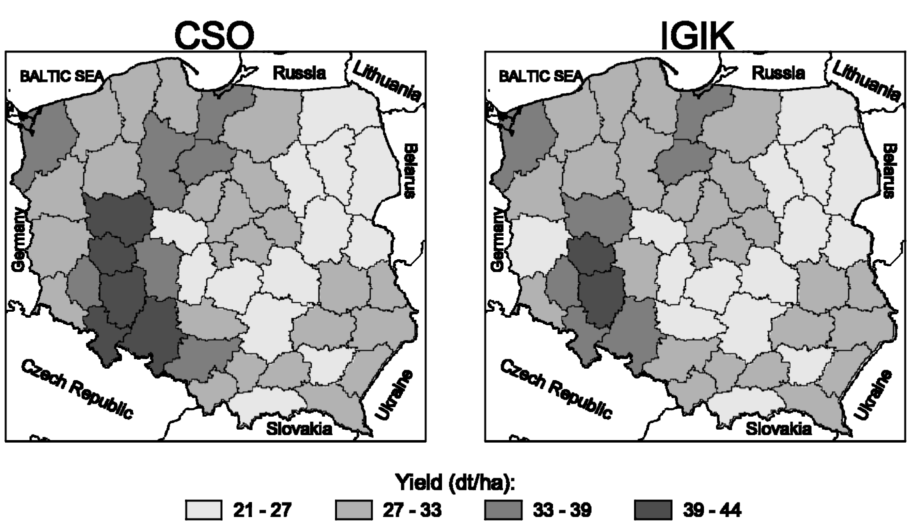

Figure 8. Results of cereals yield assessment according to the Central Statistical Office (CSO) and performed by the Remote Sensing Centre (IGIK) for 1998.

It was also found that TCI could be used to interpret soil moisture conditions on large areas. High temporal resolution of images taken by NOAA satellites makes possible to find and to monitor the areas with soil water deficit. In 1992 severe drought occurred in Poland. Unfavourable conditions at the beginning of the growth season (week 16) in central and south-eastern Poland were expressed by high values of TCI (low brightness temperature, see figure 9). In western Poland, the TCI was

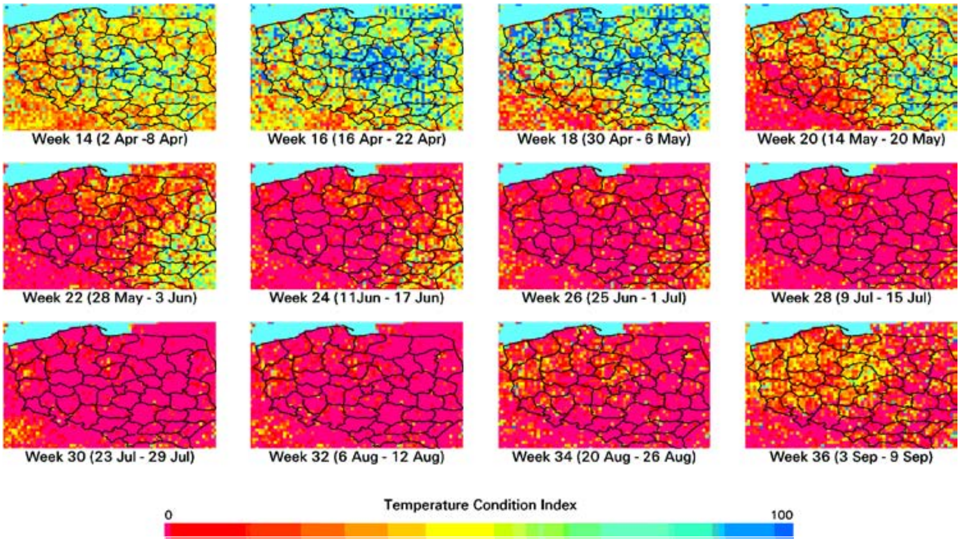

Figure 9. Temperature Condition Index in 1992.

low, indicating good conditions for crop development. In mid-May the TCI started to decrease, indicating deterioration of growth conditions, first in western Poland and thereafter, in the rest of the country. Dry conditions remained until the end of August (week 36).

Meteorological data provided by the Institute of Meteorology and Water Management revealed that from April to August 1992 total precipitation was 40–50% below normal. However, precipitation was high in eastern Poland in April, stimulating favourable conditions for development of winter wheat. According to the Institute of Meteorology and Water Management drought started in the middle of May. This situation was confirmed by observation of TCI (figure 8, week 20). In late May the drought covered the entire country (except eastern Poland). Figure 10 shows distribution of ground-measured soil moisture in early June (week 22) 1992 (Institute of Meteorology and Water Management, *Agrometeorological Bulletin*, 1992). These data corresponded well to the TCI computed for week 22. In July and August severe drought covered the entire country. In the areas of insufficient soil moisture soil water deficit for winter wheat was within the range 200–350 mm.

On the contrary, in 1991, the growth conditions were favourable (figure 11). Temperature Condition Index for the largest part of Poland in week 16 was low and high in most of the country in week 22 and further until the harvest, which resulted in high value of yield in this year (figure 2).

7. Summary and conclusions

The study undertaken for the area of sufficient water supply has shown that the indices derived from low-resolution satellite images can be successfully used for assessment of crop growth conditions, as it can for semi-arid areas. From among the two applied indices, TCI and VCI, the first was found to be more sensitive for crop yield estimates.

The investigation showed that TCI has been strongly correlated with yield of cereals. Two periods in crop development were found when TCI was shown to be

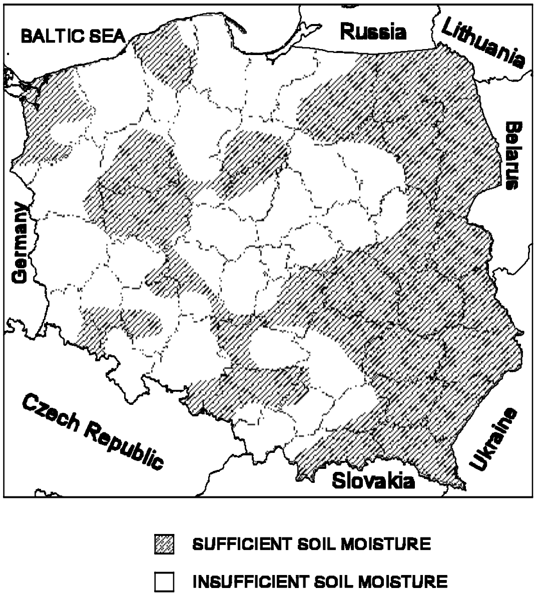

Figure 10. Map of distribution of soil moisture in Poland in week 22 of 1992 (based on ground measurements of the Institute of Meteorology and Water Management).

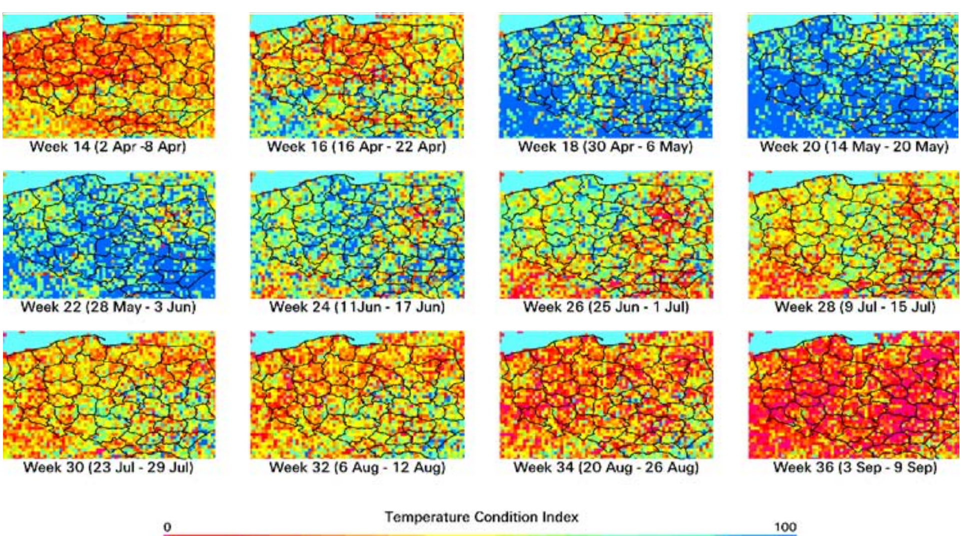

Figure 11. Temperature Condition Index in 1991.

most sensitive to detect crop conditions, which influenced crop yield. The first period occurred in weeks 14–16 while the second was in weeks 22–25 of the year. The negative correlation between cereal yield and TCI in the first period of crop growth showed that low values of TCI indicated that spring conditions were appropriate for crop development and high yield. In this case the brightness temperature (BT) was close to the maximum for these weeks.

On the contrary, the high positive correlation between TCI and crop yield in the weeks 22–25 showed that high value of TCI in this period indicates good crop growth conditions, which would reflect high cereal yields. In this time, a BT close to the maximum value of these weeks would mean non-appropriate crop conditions. The VCI calculated for week 25 gave supplementary information for crop yield estimates.

Temperature Condition Index can also be applied for drought monitoring and determination of the areas of insufficient soil moisture within the growth season.

All these findings were proved by meteorological observations done in inadequate number of points. It means that meteorological observations might be greatly improved by satellite-derived information with much greater spatial and temporal resolutions.

Acknowledgment

The authors wish to thank the Polish–American Maria Sklodowska–Curie Second Fund for financing this research.

References

Central Statistical Office, 1999, Final results of plant production in 1997 and 1998. Central Statistical Office, Warsaw.

Dabrowska-Zielinska, K., Kogan, F. N., Ciolkosz, A., Gruszczynska, M., Raczka, U., Kowalik, W., and Jankowski, R., 1998, New methods of drought detection based on NOAA satellites and its impact on agriculture. *Proceedings of ASPRS-RTI Conference*, *Tampa, Florida, USA*, pp. 1501–1504.

Hamar, D., Ferencz, C., Lichtenberger, J., Tarcsai, G., and Ferencz-Arkos, I., 1996, Yield estimation for corn and wheat in the Hungarian Great Plain using Landsat MSS data. *International Journal of Remote Sensing*, **17**, 1689–1699.

Institute of Meteorology and Water Management, 1991, 1992, 1997, 1998, *Agrometeorological Bulletins*, Institute of Meteorology and Water Management, Warsaw.

Kidwell, K. B., 1996, AVHRR data acquisition, processing and distribution at NOAA. In *Advances in the Use of NOAA AVHRR Data for Land Applications*, edited by G. D'Sousa, A. S. Belward and J. P. Malingreau (Dordrecht: Kluwer Academic), pp. 433–455.

Kogan, F. N., 1997, Global drought watch from space. *Bulletin of the American Meteorological Society*, **78**, 621–636.

Rao, C. R. N., and Chen, J., 1995, Inter-satellite calibration linkages for the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAA-7, -9, and -11 spacecrafts. *International Journal of Remote Sensing*, **16**, 1931–1942.

Rao, C. R. N., and Chen J., 1999, Revised post-launch calibration of the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAA-14 spacecraft. *International Journal of Remote Sensing*, **20**, 3485–3491.

Unganai, L. S., and Kogan, F. N., 1998, Drought monitoring and corn yield estimation in Southern Africa from AVHRR data. *Remote Sensing of Environment*, **63**, 219–232.

Weinreb, M. P., Hamilton, G., and Brown, S., 1990, Nonlinearity correction in calibration of the Advanced Very High Resolution Radiometer infrared channels. *Journal of Geophysical Research*, **95**, 7381–7388.